

Back-scattered electron imagery of the tectonic fabrics of some fine-grained sediments: Implications for fabric nomenclature and deformation processes

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ABSTRACT

Back-scattered electron investigations of Argille Scagliose, mudstones from the Barbados forearc sampled during Ocean Drilling Program Leg 110, and the matrix of the Okitsu melange, southwest Japan, indicate a variety of microfabric geometries and deformation mechanisms despite the similarity of their mesoscopic scaly fabrics. In the Okitsu melange, the scaly fabric is the mesoscopic expression of an anastomosing microfabric, whereas the detailed geometry of scaly fabrics is unrelated to the microfabric in the Argille Scagliose and Leg 110 mudstones. Care must be taken in the classification and interpretation of scaly fabrics in light of these data, and future studies should focus on microstructural investigations.

INTRODUCTION

Tectonic fabrics have been described from fine-grained sediments in numerous settings. These include studies of active forearc regions (see summary of Moore et al., 1986, 1988; Behrmann et al., 1988); onshore accretionary complexes (Bachman, 1982; Nelson, 1982; Barber et al., 1986); olistostromal and slump deposits (Boles and Landis, 1984); and the interiors of orogens (Vollmer and Bosworth, 1984). Many studies have used the terms "scaly clay" or "scaly fabric" to describe the deformation texture of low-grade, fine-grained sediments. Mesoscopically scaly fabrics are characterized by anastomosing surfaces, many of which are polished and/or striated (Moore et al., 1986).

High-resolution back-scattered electron (BSE) imagery (Lloyd, 1987) on the scanning electron microscope (SEM) is an ideal tool for the examination of fine-grained sediments (Krinsley et al., 1983; White et al., 1984; Prior and Behrmann, 1989). We have used this technique to examine fabrics in three different settings: (1) the Argille Scagliose of the Italian Apennines, (2) scaly horizons in the Barbados forearc, and (3) the matrix of the Okitsu melange of southwest Japan.

TECTONIC SETTINGS AND MESOSCOPIC CHARACTERISTICS

1. The Argille Scagliose was examined near Passo della Cisa (Page, 1963). This region is now interpreted as an accretionary complex of Jurassic to Oligocene age (B. Trevers, 1988, personal commun.). The Argille Scagliose contains a variety of mesoscopic fabric morphologies, including a weak pencil fabric, a stronger blocky fabric, and an anastomosing scaly fabric. PC12 is a sample of black shale from the core of a north-facing recumbent anticline in roadside

outcrops 100 m northwest of Passo Cirone (see Page, 1963). An anastomosing, bedding-parallel fabric is overprinted by a fabric axial planar to the fold.

2. Samples have been examined from tectonic junctions identified in Hole 671B of Ocean Drilling Program (ODP) Leg 110, close to the toe of the Barbados forearc (Masle et al., 1988). Hole 671B penetrates Oligocene to Pleistocene sediments incorporated into the Barbados forearc by frontal accretion (Masle et al., 1988; Moore et al., 1988). Sample 110-671B-014X-06 contains the surface of a thrust (thrust A) of late Miocene over early Pleistocene 128 m below sea bottom (Masle et al., 1988). No scaly fabric was observed at thrust A during core recovery, although a 1–3 cm scaly zone above the thrust is now visible in hand specimen. Sample 110-671B-059X-CC is from the basal decollement, a 50-m-thick zone of scaly fabric (Masle et al., 1988; Behrmann et al., 1988; Moore et al., 1988). The scaly surfaces in all specimens examined here are polished. A few striated surfaces have been described from Hole 671B (Masle et al., 1988) and from Deep Sea Drilling Project (DSDP) Leg 78A (Moore et al., 1986), but these samples were not examined.

3. Samples have been examined from the shale-rich matrix of the Okitsu melange in the eastern Hata Peninsula, Shikoku. The Okitsu melange is part of the Shimanto Belt, a Cretaceous to early Neogene accretionary complex (Taira et al., 1982). The Okitsu melange contains a strongly anastomosing, closely spaced foliation that is locally crenulated. The foliation surfaces are polished and locally striated. Dense arrays of quartz and calcite veins both transect and parallel the foliation. Many veins are tightly folded, and there is strong attenuation on limbs

parallel to the foliation. Sample 505 was collected from the west side of Okitsu Bay (Agar, 1987, Fig. 4.34), where large (10 m) blocks of basalt and strongly attenuated tuff and chert layers are isolated in the matrix. Sample 503B was collected 1 km to the south of sample 505 in strongly attenuated and disrupted fine-grained sandstone and shales.

METHODS

Argille Scagliose samples were set in plaster of paris and oriented before they were chiseled from the outcrop. In the laboratory, samples were impregnated with epoxy, sawed, and reimpregnated before cutting chips for examination. ODP samples were freeze dried by shipboard staff immediately after core recovery. Specimen-polishing techniques described by Prior and Behrmann (1989) were employed. High-resolution BSE images were obtained by using a Camscan Series 4 SEM with a four-quadrant, solid-state ring detector at working distances between 4 and 7 mm, accelerating voltages of 20 to 30 kV, and a beam current of 175 nA. Porosity values quoted from BSE images are underestimates (D. Prior and J. Behrmann, in prep.).

MICROFABRICS

Microfabric of the Argille Scagliose

The Argille Scagliose is composed of 20% to 50% phyllosilicates (0.5–3 μm) and 10%–15% pore space (Fig. 1). The remainder comprises clasts of quartz (1–15 μm) and calcite (0.25–10 μm) in ratios of 1:1 to 1:3. Phyllosilicates intergrown with quartz and calcite are Ca-montmorillonite. Quartz and predominantly fossiliferous calcite clasts are mostly elongate (Fig. 1). The specimens also contain pyrite framboids, up to 30 μm (comprising round particles less than 0.5 μm), 3 to 5 μm cubic pyrites, plagioclase, and apatite.

Mesoscopic fabrics are defined by fractures. The predominant fracture orientations are controlled by the microfabric, but the location of these fractures does not reflect microfabric intensity, and the detailed fracture geometry does not correspond to microfabric geometry.

Microfabric is most strongly defined by the alignment of elongate grains (Fig. 1). Phyllosili-

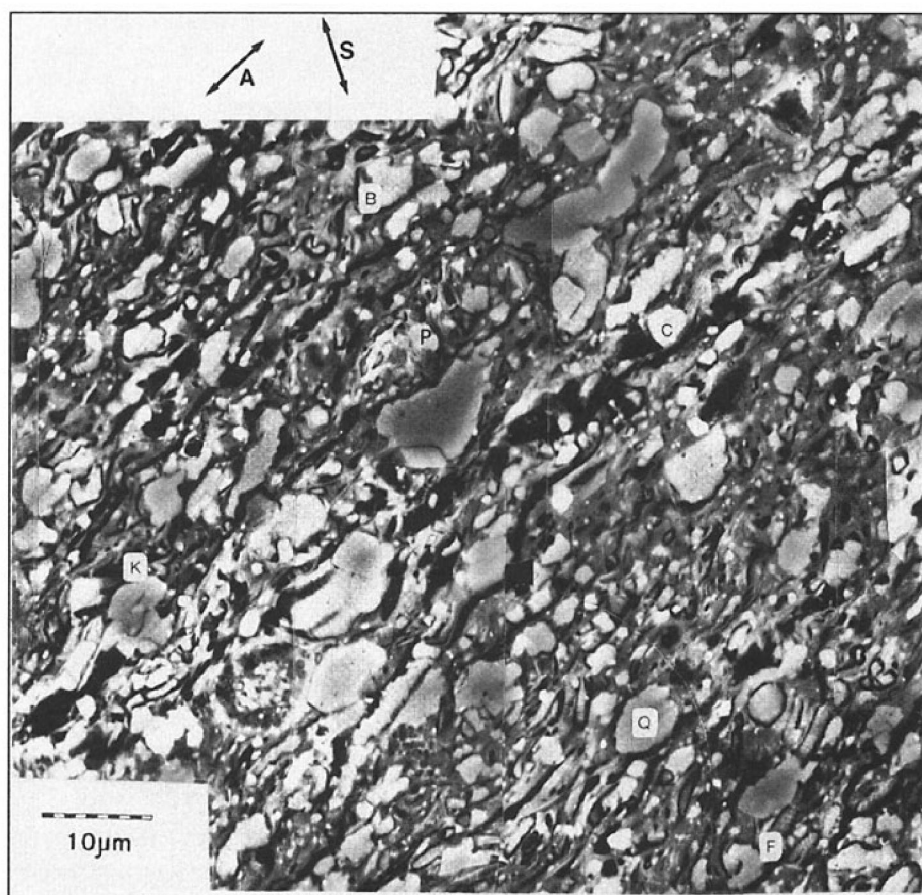


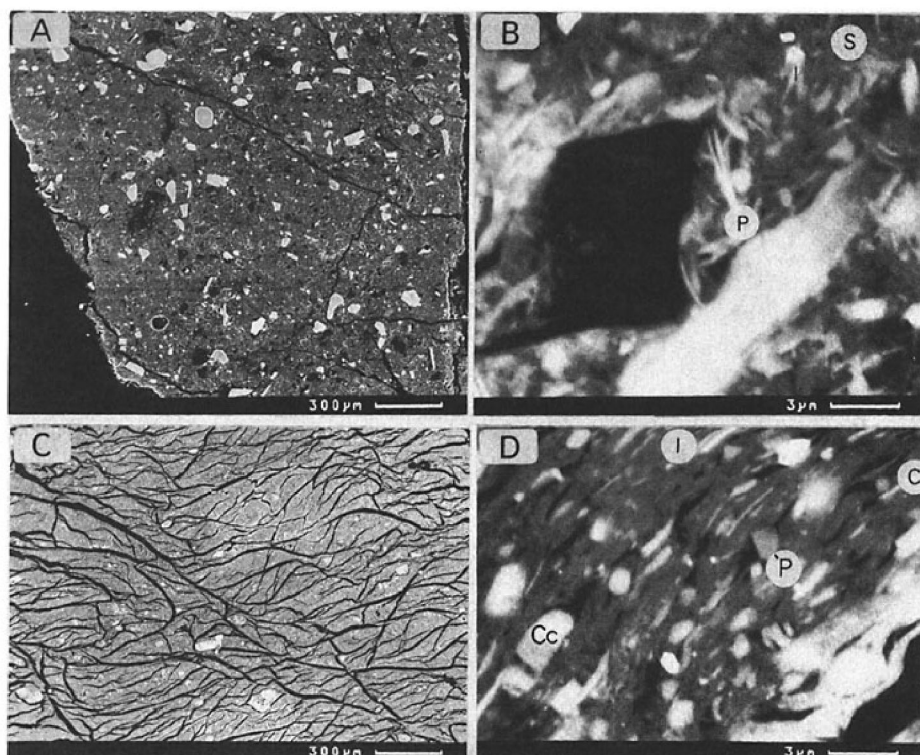
Figure 1. Montage of BSE micrographs from core of macroscopic fold of Argille Scagliose (specimen PC12). S: Earlier bedding-parallel fabric is overprinted by strong axial planar fabric (A). P: Pods in which earlier microfabric is preserved. Microfabric is defined by alignment of quartz (Q) and calcite (C) long axes, particularly tests of forams (F). Small grains impinge into some calcite clasts. Phyllosilicate fabric is generally aligned with long axes. Phyllosilicates are buckled around clasts (B) and folded and kinked into spaces between clasts (K). Small, round, bright phases are pyrite framboid particles. Black areas are epoxy-filled pore space.

cates are generally aligned with the clasts but anastomose on a micron scale around some clasts and are locally folded and kinked (Fig. 1). An early bedding-parallel fabric is refoliated in the axial plane of the fold. Within the axial planar fabric are pods (10 μm by 50 μm) in which the early fabric is preserved (Fig. 1). The early and later fabrics are microstructurally similar, suggesting that their formation resulted from similar mechanisms at similar conditions. Locally, phyllosilicate fabrics are overgrown by irregular calcite and quartz grain margins. The impingement of small grains of quartz, calcite, and pyrite into large calcite grains indicates that pressure solution is an important deformation mechanism. Pressure solution and overgrowth sites are likely to be the source and sink of diffusive mass transfer (DMT) processes. No structures indicate noncoaxial shear.

Microfabric of Mudstones from the Barbados Forearc

Sample 110-671B-014X-06 from thrust A comprises 60% to 80% phyllosilicates (0.2–3 μm), up to 20% pore space, and clasts (1–100 μm) of calcite and plagioclase. Phyllosilicates are a mixture of smectite, illite, and some chlorite (Fig. 2). A scaly fabric now present in the sample is defined by curvilinear fractures (Fig. 2C). The relation between scaly fabric and phyllosilicate microfabric is complex. In the footwall of thrust A there are few mesoscopic fractures (Fig. 2A) and no preferred phyllosilicate orientation (Fig. 2B). In the hanging wall the spacing and alignment of fractures (Fig. 2C) decrease upward, corresponding to a change from a strong preferred orientation of phyllosilicates

Figure 2. BSE micrographs at low and high magnification of specimen 110-671B-014X-06 from Barbados forearc. Specimen contains thrust (thrust A) of late Miocene over early Pleistocene age rocks (Masle et al., 1988, Fig. 3, p. 74). A: Early Pleistocene, 3 mm below thrust, illustrating lack of mesoscopic fabric. Large bright clasts are mostly plagioclase. B: Close-up of center of A showing lack of alignment of clay-size particles. Phyllosilicates are illite/smectite (Ca-montmorillonite) mix. Bright phyllosilicates (I) are illite; darker phyllosilicates (S) contain significant smectite interlayering. Brightest elongate grains (P) are platelets of calcite of organic origin. Black rhomb-shaped area is hole left by pyrite grain that fell out during preparation. C: Late Miocene 1 mm above thrust. Scaly fabric is defined by anastomosing curvilinear fracture surfaces. Large bright clasts are mostly calcite fossil tests. D: Close-up of center of C. Strong foliation is defined by pervasive alignment of illite (I), some chlorite (C), and clasts of calcite (Cc), and plagioclase (P), which do not correspond to mesoscopic scaly fabric.



(Fig. 2D) to a moderate preferred orientation of phyllosilicates. However, the phyllosilicate fabric orientations are not related to the fracture surfaces. The phyllosilicates do not form anastomosing planes corresponding to fracture surfaces. Where microfabric is strongly developed it is generally pervasive with orientation variations relating only to the presence of clastic material. No microstructures indicate noncoaxial shear.

The phyllosilicates (0.2–3 μm) in specimen 110-671B-059X-CC from the decollement zone comprise smectite, illite, and some chlorite, and form 70% to 80% of the rock volume; the remainder consists of clasts (1–20 μm) predominantly of calcite, and some plagioclase and quartz (Fig. 3). These specimens contain a scaly fabric comprising an irregular, anastomosing network of curvilinear fracture surfaces. However, no part of the specimens from the decollement shows any alignment of phyllosilicates or clasts. The phyllosilicates in the decollement zone characteristically have a random, hairy texture.

The decollement zone of the Barbados forearc has deformed without development of grain alignment, suggesting that independent particulate flow (IPF, Borradaile, 1981) is the predominant deformation mechanism.

Microfabric of the Okitsu Melange

Phyllosilicates compose 20% to 75% of the melange matrix, depending upon the distribution of incorporated clasts (50 to 5000 μm). Porosity is generally less than a few percent, although it is locally enhanced by unfilled fractures. Semi-quantitative X-ray diffraction (XRD) analysis (Agar, 1987) shows that phyllosilicates comprise mainly illite (70%–80%), chlorite (10%–16%), and kaolinite (10%–16%).

Fabrics are defined by zones of phyllosilicate alignment and seams of dark residuals (probably hydrated iron oxides). Residual seams are characteristic of DMT processes (Borradaile et al.,

1982). Some clasts have tapered ends caused by quartz overgrowths or beards of neomorphic micas. In sample 505, many of the clasts have a weak sigmoidal geometry (Fig. 4A) consistent with shear-sense indicators at outcrop (Agar, 1987). Strong lattice distortion in the clasts of fragmented vein quartz in sample 505 suggests that crystal plasticity has contributed to deformation within the matrix. Clast margins are often embayed and offset by through-going fractures. In regions where detrital clasts are scarce, narrow domains of phyllosilicate alignment are deformed by shear bands (2 μm) oriented at low to moderate angles to the dominant fabric (Fig. 4B). These give rise to anastomosing fabric geometry. Some shear bands are localized on margins of clasts. Early DMT seams and veins are isoclinally folded. In such zones foliation is often reactivated.

In less strongly deformed lithologies to the south of Okitsu (Agar, 1987), extremely elongate clasts show little intragranular deformation. This suggests that much of the early attenuation may have been accomplished by IPF (Borradaile, 1981) in partially consolidated material.

DISCUSSION

Within the three examples discussed, the scaly fabric and the microfabric are commonly not defined by the same fabric elements. In the Leg 110 specimens and the Argille Scagliose, scaly fabric is defined by curvilinear fractures that isolate domains of phyllosilicates and small detrital clasts, but do not, in general, relate to the microfabric. In contrast, the microfabric and scaly fabric of the Okitsu melange are both defined by anastomosing seams of phyllosilicate and clast alignment and DMT seams.

Contrasting deformation processes responsible for the microfibrils of the Argille Scagliose, Leg 110 mudstones, and the Okitsu melange are evident from these BSE studies. Crystalline plasticity is only inferred in the Okitsu melange specimens. There is no evidence for DMT in the Leg 110 specimens, whereas this process has been important in the Argille Scagliose and the Okitsu melange. Particulate flow is likely to be the predominant mechanism in the Barbados forearc. The three areas examined probably relate to different structural levels in an accretionary environment. The deformation mechanisms inferred from Barbados, the Argille Scagliose, and the Okitsu melange represent a possible evolutionary sequence of deformation behavior during progressive accretion and burial to deeper, warmer conditions. In addition, many of the inferred mechanisms are sensitive to changes in parameters, such as pore-fluid pressure and strain rate (Knipe, 1986c), which are likely to vary independently of burial depth. Thus, individual specimens can show cyclical variations of predominant deformation mechanisms (Knipe, 1986a, 1986b; S. Agar, in prep.). In the specimens deformed at deeper levels, the record

of earlier, shallow-level deformation processes are wholly or partially obliterated. In the Okitsu melange, for example, we can infer early IPF from the extreme attenuation of some clasts without intragranular deformation (Agar, 1987).

Scaly fabrics from Barbados and the Argille Scagliose remain an enigma because their detailed geometry does not correspond to the microfabric. In a detailed study of cores from several active margins, Moore et al. (1986) concluded that scaly fabrics developed preferentially in fault zones. This is supported by the data from the Leg 110 cruise (Masclé et al., 1988; Behrmann et al., 1988). Some scaly fabric surfaces have striations, suggesting that they may have been slip surfaces. Secondary electron (SE) SEM imaging has shown anastomosing phyllosilicate microfibrils associated with scaly surfaces in specimens from southern Mexico (Moore et al., 1986), indicating that some scaly fabrics from shallow-level environments do reflect microfabric. Experiments by Maltman (1987) revealed that “planar, complex zones of particle re-orientation” could be generated dur-

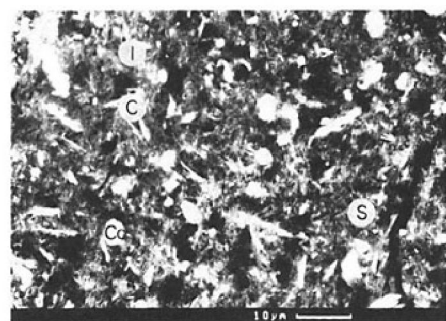


Figure 3. BSE micrograph illustrating microfabric of decollement zone of Barbados forearc (specimen 110-671B-59X-CC). Phyllosilicates have no preferred alignment and form hairy texture. Most phyllosilicates are smectite (S) (Ca-montmorillonite), with some illite (I) and chlorite (C). Clasts are mostly calcite (Cc).

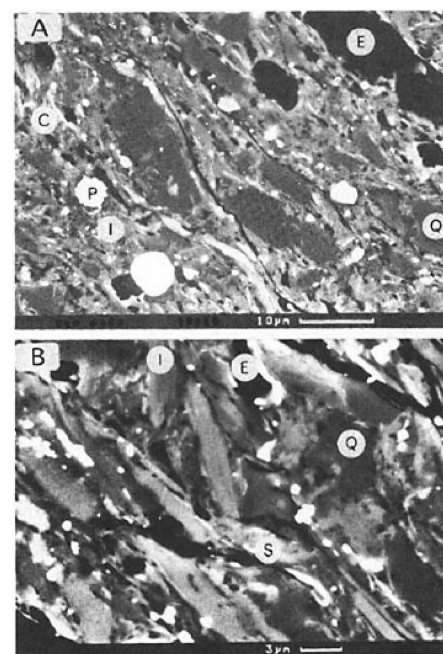


Figure 4. BSE micrographs of Okitsu melange matrix. A: Attenuated clast fragments neighboring large detrital clast (off picture, specimen 505). Illite (I) and chlorite (C) are dispersed in matrix with fine bright pyrites (P). Fragments comprise mainly vein quartz (Q), with patches of illite and chlorite. Asymmetric tails of illite and quartz overgrowths extend from ends of clast, giving weak sigmoidal geometry. (E = epoxy-filled crack). B: Narrow extensional shear (S) deflecting interlayered chlorite and illite flakes (specimen 503A). Shear plane curves into main foliation direction near base of photo. Specimen comprises quartz (Q), large illite-smectite interlayered grains (I), and sub-micron matrix of smectite and illite with bright pyrites (E = epoxy-filled pore space).

ing wet-sediment deformation, and that arrays of shear zones would form as older zones lock up, to give an anastomosing appearance. Because the term "scaly fabric" has been frequently used in relation to DSDP/ODP studies of wet-sediment deformation in forearcs, the connotation of noncoaxial shear with the use of "scaly fabric" has become commonplace. There are documented examples of shear zones in naturally deformed sediments (Maltman, 1988); however, we think that it is important to examine individual fabrics microstructurally to determine how the fabric has formed. Shearing processes should not be assumed.

Van den Berg (1987) reported that laboratory fracture of experimentally deformed specimens did not occur along the slip plane, suggesting that we need not expect specimen fracture to relate to microfabric. The BSE evidence from Leg 110 mudstones shows no modification of microfabric at scaly surfaces, and there is no evidence of displacement across scaly surfaces. Alternative mechanisms to those inferred in microfabric development are required to explain the scaly fabrics. Those at thrust A in Hole 671B were not present on core recovery and are probably artifacts of specimen preparation. The scaly fabrics in the Barbados decollement and the Argille Scagliose cannot be explained as easily. One possibility is that some of the anastomosing and irregular sets of fractures in these specimens are stress-release features (Nichols, 1980) and their intensity and orientations may be reflections of in situ stress magnitudes and orientations (D. Prior and J. Behrmann, in prep.).

SUGGESTED TERMINOLOGY

The mesoscopic and microscopic fabrics of tectonized fine-grained sediments can relate to different processes and different periods of rock evolution. We think that it is important to clarify the scale at which observations are made and to use a more precise terminology. There are well-defined and documented terms to describe the geometry of mesoscopically anastomosing fabrics, such as the qualifiers "parallel," "sinuous," "anastomosing," "trapezohedral," and "conjugate" suggested by Borradaile et al. (1982). Although the term "scaly fabric" may still be appropriate as a field description, it is important that this term not be used to refer to fabrics on the scale of grains. We suggest that the term "microfabric" be used exclusively for this purpose, with qualifiers from existing cleavage terminology (Borradaile et al., 1982).

FUTURE DIRECTIONS

Future investigations of sediment microfabric should focus on BSE studies, coupled with examination of intragranular microstructure using transmission electron microscopy (Smart and Tovey, 1982; Knipe, 1986a, 1986b) to evaluate, in detail, the processes involved in the develop-

ment of microfabric. A major goal of such studies should be the establishment of detailed deformation mechanism paths (Knipe, 1986c), which will lend invaluable data to the understanding of the interaction of tectonics, sedimentation, fluid processes, and diagenesis in tectonized fine-grained sediments.

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